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New Method of Surface Settlement Prediction for Saint-Petersburg Metro Escalator Tunnels Excavated by EPB TBM

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Abstract

The article describes a new technology of escalator tunnel construction using earth pressure balance tunnel-boring machines (EPB TBM) in complex geological conditions of St. Petersburg soils. The results of field surveying observations of settlements and strain calculations arisen from the construction of the escalator tunnels of the St. Petersburg metro "Obvodny kanal", "Admiralteyskaya", "Spasskaya" stations are presented. It is established that the evolving strain can be dangerous for undermining buildings and structures. The method of escalator tunnel construction numerical modeling based on the finite element method is used to evaluate the qualitative relations of the geomechanical processes. A new method of surface settlement prediction is based on the results of complex processing of field data and results of construction numerical modeling. This method involves determination of the following characteristics of the displacement process: the position of the point of the maximum settlement in a subsidence trough, the size of a subsidence trough, the value of the maximum settlement, distribution of displacements and strains in the trough. The developed method for calculation of the settlements was tested on Saint-Petersburg metro escalator tunnels. Comparison of results for predicted and observed data indicate the reliability of the developed settlement and deformation prediction method in the construction of the escalator tunnels using the TBM in St. Petersburg.

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Keywords: escalator tunnel; EPBM; surface settlement prediction; subsidence trough; FEM; modeling.

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1. Introduction

In recent years, modern technology of driving escalator tunnels using tunnel-boring machines with earth pressure balance shield (EPB TBM) is implemented in the practice of civil engineering in Moscow and Saint - Petersburg. This technology significantly reduces the harmful effects of tunneling on the earth's surface (Fig. 1).

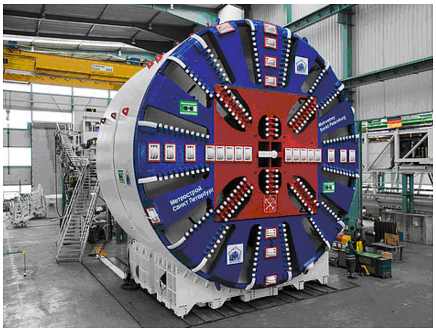

Fig. 1. EPB TBM «Aurora»

However, the field observations shows that the strains formed on the earth's surface are dangerous for undermining buildings and structures. According to settlement monitoring data on groundwater reference points, in the construction of the escalator tunnel "Spasskaya" station dimensions of displacement trough were up to 80 m in the longitudinal and transverse directions. Maximum settlements reach up to 50 - 60 mm in compliance with technology regulations of construction and in case of irregularities in technology it can be up to 100 mm.

The relevance of research is confirmed by the fact that the method of surface settlement prediction for the escalator tunnel excavated by TBM in complex geological and mining conditions of St. Petersburg still does not exist. Leading scientists were engaged in research of displacement process of coal mines [1-5]. Problems of estimation of surface settlement in urban tunnel construction are considered in works [6-11], but these works do not describe the specificity of inclined tunnels driving using TBM. Taking into account above-listed, the problem of developing method of surface settlement prediction during construction of the escalator tunnels using TBM is relevant.

2. Results of the field mine-surveying observations

Results of the field mine-surveying observations during the construction of the stations of the St. Petersburg Metro "Obvodny kanal", "Admiralteyskaya," "Spasskaya" were adopted as the basic data for research. In addition to estimation of settlements in the research were calculated maximum values of deformations of inclination and curvature deformation. Thus, for the escalator tunnel of the "Spasskaya" station the maximum surface settlement amounted to 57 mm, the deformation of the inclination $i = 2{,}5 \cdot 10^{-3}$, the curvature deformation $k = 2{,}4 \cdot 10^{-4}$1/m (Fig. 2). For the escalator tunnel of the "Admiralteyskaya" station the maximum surface settlement amounted to 48 mm, the deformation of the inclination $i = 2{,}6 \cdot 10^{-3}$, the curvature deformation $k = 1{,}8 \cdot 10^{-4}$ 1/m. For the escalator tunnel of the "Obvodny kanal" station the maximum surface settlement amounted to 93 mm, the deformation of the inclination $i = 6{,}4 \cdot 10^{-3}$, the curvature deformation $k = 14 \cdot 10^{-4}$ 1/m. The values of the deformation, calculated based on the field observations, are much higher than the critical deformations of inclination and curvature that define the area of dangerous influence according to the "Rules on protection of facilities and natural sites against a hazardous effect of under-ground mining in coal deposits" [12].

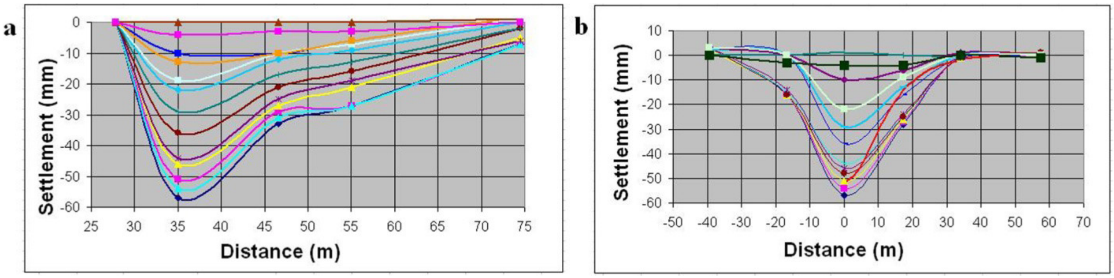

Fig. 2. Development of subsidence during the "Spasskaya" escalator tunnel construction: a) in the main longitudinal section; b) in the main cross-section

During the construction of the escalator tunnel in St. Petersburg were used different types of displacement process monitoring: traditional observations using ground reference points and benchmarks set out in the buildings, the use of downhole systems with extensometers to monitor the settlement of the massif, and hydrostatic pressure monitoring system in the massif [13-15]. Though the wide range of methods of the field observations, they do not allow to evaluate the picture of the geomechanical processes in general, and to develop a reliable method of surface settlement prediction. Hence for determination the main qualitative regularities of the displacement processes in the massif and on the earth's surface was used numerical modeling based on the finite element method (FEM). Only such a comprehensive approach let explore the mechanism of the deformation processes in the rock massif, analyzing quantitative and qualitative component of the displacement process [16-18].

3. Three-dimensional modeling of escalator tunnel driving

For purposes of qualitative patterns of development of displacement and deformation processes in rock massif investigation were implemented different model types used in software finite element modeling Plaxis 3D linear-elastic model, Mohr-Coulomb, hardening soil HS [19]. Total amount of models is more than 300. As a result of a series of calculations of multiple objects with different behaviors of materials hardening soil models showed most internal convergence and affinity results of field observations. These models subsequently were adopted as the basic computational models to all escalator tunnels. An example of a model for the calculation of displacements and deformations for the escalator tunnel driving based on finite element method is shown in Figure 3. Constructed models verification was carried out using the field observation surveying data obtained during the driving of escalator tunnels of underground stations "Obvodny kanal", "Admiralteyskaya," "Spasskaya".

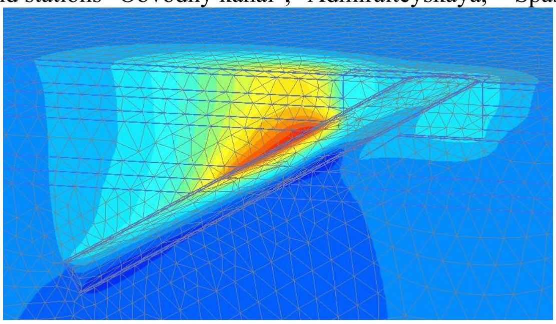

Fig. 3. Distribution of vertical displacements in the model of escalator tunnel driving

The method of standard settlement curves was applied to investigate the patterns of movement in the displacement trough, built on the results of field observations, as well as simulation results. This method is traditionally used in mine surveying to evaluate displacements and deformations [20].

4. New method of surface settlement prediction

Result of the research was the development of engineering method of surface settlement prediction, which includes determining the following characteristics of the displacement process: the position of the point of maximum settlement in subsidence trough, size of subsidence trough, the value of maximum settlement, distribution of displacements and deformations in the trough [21].

Determination of maximum settlement point position in subsidence trough was based on the results of mathematical modeling. Experimental results have shown, the position of the point of maximum settlement should be defined as a projection to the earth surface the intersection point of the tunnel axis and the lower boundary of the "weakened" layer (Fig. 4). The absolute error in determining the position of the point of maximum settlement is in the range of 2 - 5 m for different conditions of tunneling.

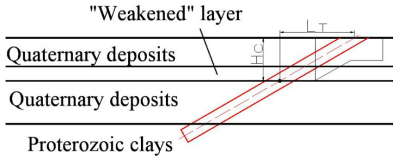

Fig. 4. The scheme to determine the position of the point of maximum settlement

Position of the point of maximum settlement can be determined by the formula:

$$L_T = k \cdot H_c \tag{1}$$

where L_T is the distance from tunnel axis on the earth's surface to the point of maximum settlement and H_c is a thickness of Quaternary sediments from the bottom of the "weakened" layer; k=ctg30°≈1,73.

Subsidence through size is calculated depending on the boundary angle values according to the formula:

$$L = (H_T + h) \cdot ctg\delta_b + l \tag{2}$$

where L is a subsidence trough size, m; H_T is a thickness of Quaternary sediments overlying the tunnel axis, δ_b is the boundary angle, degree; h and l are vertical and horizontal distance from the tunnel axis to a point on the contour of the tunnel from which the limiting angle is drew on a tangent; h=4.9 m, l=3.5 m.

Boundary angle is determined depending on the thickness of Quaternary sediments in the massif by the formula:

$$\delta_b = a \cdot H + b \tag{3}$$

where H is a thickness of Quaternary sediments, a and b are coefficients (to review the conditions of escalator tunnel driving in St. Petersburg, a=-0.57; b=54.37).

Equation for estimating the maximum surface settlement value is represented according to S.G. Gutman [22, 23]:

$$\eta_{\max} = q \cdot u_{sv} \tag{4}$$

where η_{max} is the maximum surface settlement value, u_{sv} is the maximum total displacement of rock tunnel arch (as an integral component of convergence), q is a coefficient from the solution by prof. S.G. Gutman.

The maximum displacement of the tunnel arch u_{sv} species is determined by the observations of bore hole reference points (application of interpolation method is possible).

To estimate the maximum surface settlement value at the end of settlement process with the additional settlement due to the rheological processes, it is proposed to use the qr coefficient determined by the formula:

$$q_r = Ke \cdot q + Ce \tag{5}$$

where *Ke*, *Ce* are empirical coefficients obtained by the field observations during the driving of escalator tunnel at the end of the displacement process in the rock massif. For mining and geological conditions of the escalator tunnel driving in St. Petersburg there are: *Ke*=1,87; *Ce*=0,02. The results of geomechanical modeling of movements when driving the escalator tunnels in various conditions confirm the validity of these relationships with the error up to 8-10%.

Patterns of distribution of movements in the trough were investigated using regression analysis of settlements received the full data for escalator tunnel construction of in St. Petersburg. The distribution function of settlements in subsidence trough is as follows:

$$S(z) = (1-z)^{a \cdot z^b \cdot e^{cz}} \tag{6}$$

Where $z=x/L$ (*L* is the subsidence trough length, x is the abscissa of the point considered (the coordinate origin at the point of maximum settlement)), *e* is the base of natural logarithms, *a, b, c* are constant coefficients.

The coefficients of the standard curve were determined in the research: a = 18.9; b = 1.90; c = -2.58. The graph of standard function is shown in Figure 5.

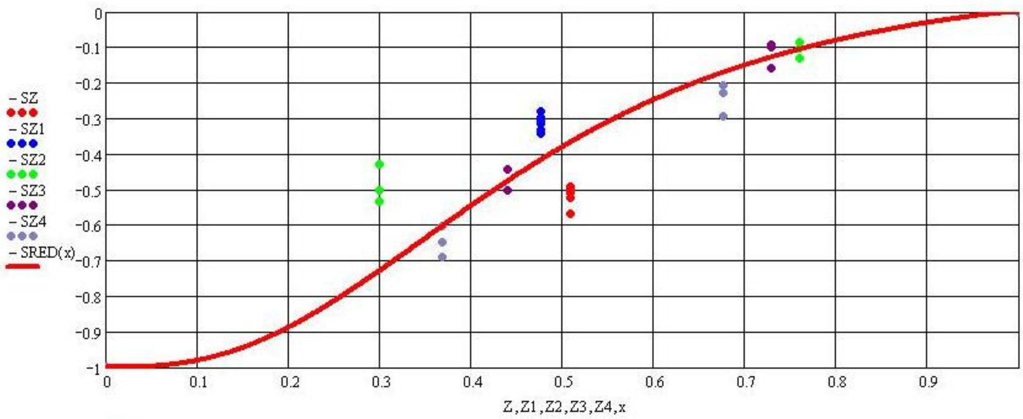

Fig. 5. Typical Settlement Curve

Deformations of inclination *i(z)* and curvature *k(z)* at points of displacement trough using the function proposed in formula 6 can be expressed as follows:

$$i(z) = \frac{\eta_{\max}}{L} \cdot S'(z) \tag{7}$$

$$\mathrm{k}(z) = \frac{\eta_{\max}}{L^2} \cdot S''(z) \tag{8}$$

where *S'(z), S''(z)* are the derivatives of *S(z)* in the *z*.

5. Conclusions

Integrated use of field data and the results of multivariate mathematical modeling to verify the model allow to develop of the engineering method of surface settlement prediction for the escalator tunnels construction using

TBM. Using the described method will increase the efficiency of the harmful effects prediction of underground construction and will improve safety while undermining buildings.

Results of the predicted and actual subsidence troughs comparison are shown in Figure 6.

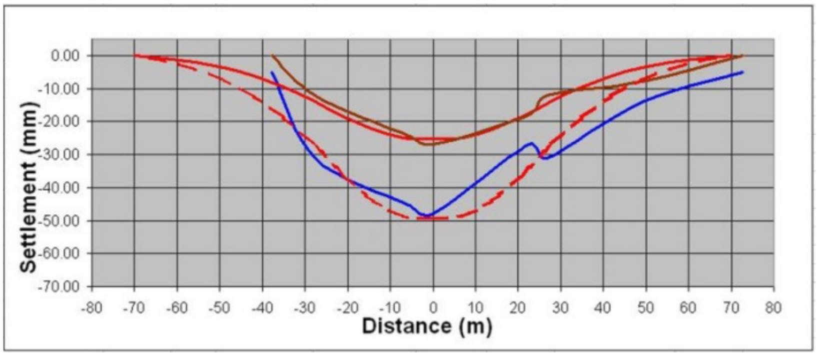

Fig. 6. Comparison of the predicted and the actual displacement trough at the end of tunneling and at the end of subsidence process

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